TELEOPERATION STRATEGIES FOR EXPLORING AND UTILIZING THE RESOURCES OF SPACE

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Abstract

The exploration and exploitation of space will require an optimal combination of human beings and machines. The latter may be either on-site, or a long distance from the space-based activity. Sending sensory input to, and receiving direction from, human beings at a remote location is known as telepresence and teleoperation. Its uses will include mining and processing lunar materials, assembling large space structures, and assisting in remote emergency surgery. Extraterrestrial teleoperation is constrained by the velocity of light, whose round-trip travel time between the Earth and the Moon is 2.6 seconds. The cutting edge in teleoperated terrestrial surgery is described. Visual feedback in teleoperation is limited by latency, computational and bandwidth requirements, image generation lag, operator fatigue, etc. Sound feedback can overcome some of these limitations. Teleoperational methods being developed for terrestrial surgery can be extended to various space-based activities. To handle these different tasks, various teleoperation strategies are described. Serving in place of gravitational cues, perhaps virtual audio can help us navigate on the high frontier.

Introduction

One of the key issues in the planning of a space-based operation is the appropriate use of human beings and machines. Although many tasks in space will be fully automated, many others will require a human presence. The roles of human beings and machines are usually devised to balance several needs, such as cost constraints, the dangers of various space environments, and the usefulness of human perception, decision-making, and adaptability. In situations where human skills are needed, but human vulnerability or cost constraints prohibit a direct human presence, it may be possible for a human being to project his/her skills into a distant environment through a radio link. This will involve the use of machines sending sensory input to, and receiving direction from, human beings at a remote location. This is referred to as telepresence and teleoperation. Teleoperation may also be useful in situations where the number of human beings present is limited. For example, a crew of, say, four persons on a Mars mission may need various medical specialists, but it would not be feasible to send them on the mission. One of the characteristics of modern medicine is the huge variety of diagnostic tests and treatment methods available. Indeed, a modern operating room may itself be larger than the pressurized volume in a space vehicle of the near future.[1] A lone surgeon may need to call on the assistance of colleagues on Earth. These Earth-bound physicians will have access to huge amounts of information from onboard cameras and advanced patient monitoring devices. The latter could be worn as undergarments[2] or be permanently implanted in the bodies of crew members.[1] The huge flow of data will have to be managed, and presented to physicians in a way that does not cause sensory overload. Medical procedures can be developed for situations that arise on Earth, and can then be extended to the space environment. For example, the costs of surgery in remote places such as Antarctica in the winter make the development of telesurgery not only lifesaving but economical. Any space-based construction or colonization will have its share of medical/surgical emergencies. It is incumbent on us to investigate ways to project life-saving talent into orbit via bits instead of mass.

A major physical constraint on teleoperation is the velocity of light. If a human being transmits an instruction to a robot on the Moon, and the robot transmits a picture of its response to the Earth, the operator will not see the response until 2.6 seconds after the instruction was sent. This represents the round-trip travel time for radio signals traveling between the Earth and the Moon. It has been shown that the teleoperation of a robot arm using visual feedback is feasible under such conditions[3] (see also, Ref. 4, Appendix 2, pages 313-326). However, the delay time between Earth and Mars will be several minutes, rendering such teleoperation less feasible. Furthermore, surgery and other medical procedures will require haptic (force) feedback, as well as visual feedback, and will be less forgiving of errors. Haptic feedback in surgical procedures must usually be limited to delays of no more than a few milliseconds, although there may be ways of circumventing this in some circumstances. The feasibility of teleoperation depends on three major factors:

- the nature of the task itself;
- the distance over which teleoperation is to take place;

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- the type of feedback (visual, sound, haptic) that is available to the teleoperator.

Both the space and the surgical environment may benefit from novel approaches to providing feedback.

Human Factor Limitations on Visual Feedback

Real-time visual images have been the most widely-considered form of feedback in teleoperation, simulation, and other computer-assisted systems. Computer-generated imagery can either augment or replace the unassisted visual field. Such systems may consist simply of a color or monochromatic monitor, or may involve more "immersive" visual devices, such as head-mounted/heads-up displays. The latter may be useful in adding computer-generated icons to a "real world" visual image. The sophistication of computer-generated images is limited by the need to render them in real time. Displays are limited in terms of scan rate and resolution, and in the case of head-mounted displays, comfort. Latency (time delay) in image generation and dynamic head tracking can cause synthetic imagery to "lag behind" real world imagery. For a see-through head-mounted display, this will lead to a mismatch between the computer-generated image and the "live video" of the surroundings. Nausea, or "simulator sickness" can result from these lag times, and other discrepancies between perceived and expected motion cues, such as the absence of vestibular (inner ear) feedback (since the eyes may perceive motion while the inner ear will not).[5,6,7] The solution of one of these problems may exacerbate others. For example, visual displays must operate at speeds greater than 30 frames per second in order to prevent flickering. However, increasing the frame rate will increase computational requirements and add to lag time in the generation of images. Even without the necessity of combining live and computer-generated images, lag times of significant fractions of a second will make computer-assisted surgery unfeasible. Although the improvement of visual systems has been the subject of extensive ongoing research, the use of audio feedback in virtual systems has been relatively unexamined until recently. Researchers at Computer-Aided Surgery, Inc. (CASI) are currently exploring the use of auditory cues as an aid in terrestrial surgery.[8,9,10,11,12] Researchers at CASI and New York University propose to extend these techniques to space-based surgery, as well as to other space-based operations, such as mining and construction.

Advantages of Auditory Feedback

There are several advantages to incorporating audio feedback in virtual and teleoperation systems. Computational and transmission bandwidth requirements are substantially smaller than for visual systems. Auditory perception is omnidirectional, making it possible for the operator to localize sounds coming from behind him/her, as well as from behind objects in the visual field. The traditional use of sound as a warning (e.g., car horns) exploits this property. Vertigo and "simulator sickness" do not occur in audio systems. Visual systems, while necessary, tend to become saturated with information, and human beings using them can suffer sensory overload. Durand Begault points out that "with an audio display, the focus of attention between virtual sound sources can be switched at will; vision, on the other hand, requires eye or head movement."[13] We therefore propose to use audio systems to augment, but not to replace, visual systems.

Sound has been used to reinforce or replace other senses, such as in musical user interfaces (MUI's) for the blind[14], warning systems for civil aircraft[15], and audio feedback systems for medical equipment.[16] The use of sound to provide positional information can be seen as the inverse of the playing of variable-pitch musical instruments, such as the violin or trombone. With such instruments, which lack a mechanism for providing discrete pitches, the musician must position his/her hands extremely precisely along one axis to control the pitch of the sound. Three-axis positioning of the hands is necessary to play the theremin, an electronic instrument invented in 1928 by Leon Theremin.[17] The musician controls pitch and amplitude by moving his/her hands in space, relative to two antennae. In some instruments, the hand must be positioned to within fractions of a millimeter. Evidence suggests that the inverse process, using sound to control position, can provide feedback precise enough for surgery, or precision manipulation of mechanical components for construction purposes.[9, 10, 11, 18]

An Experimental Teleoperation System for Terrestrial Surgery

Researchers at Computer Aided Surgery, Inc. (CASI) are currently investigating alternative approaches for representing information in telemanipulation and telementoring applications for surgery. The use of programmatically generated audio feedback, in a synesthetic paradigm (synesthesia from Greek: syn = together + aisthesis; defined as a "...physical experience of a cross-modal association"[19]), has proven to be promising both for reducing bandwidth requirements, and for creating an ergonomic interface. While there is no disputing the importance of visual cues in performing intricate telemanipulations, we find[12] that it is feasible to use audio feedback for reinforcing awareness of instrument translation and rotation relative to 3D computer models, such as a pre-planned surgical tool path.

We discuss an implementation of an audio guidance system for remote surgical manipulation. This system consists of an electromagnetic tracking device, a workstation-quality computer, and a MIDI (Musical Instrument Digital Interface) audio synthesizer. For space-based applications, this

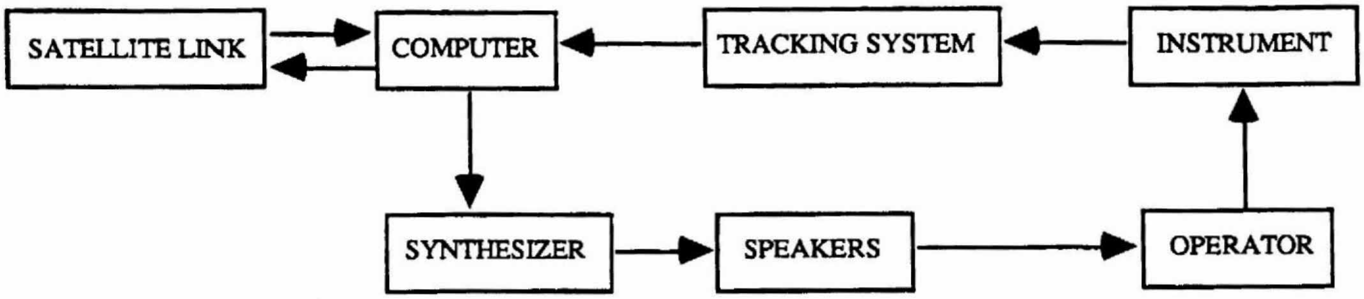

Fig. 1. Audio user interface feedback loop. Without the satellite link, the figure represents an audio guidance system for terrestrial surgery. The addition of the satellite link can extend this system to space teleoperation for surgery and other purposes.

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system would function as the Earth-bound operator's workstation. A satellite link would project the operator's intentions to a remote location (Fig. 1).

In order for the operator's gestures to have any effect upon the synthetic environment, there must be a way to track and convert the operator's movements into a machine-readable form. The ideal approach would be to use gloves equipped with sensors, so that the surgeon could remotely grasp a wide range of available objects, but a more practical approach is to instrument a surgical tool. The surgical tool can serve either as an actual scalpel, or a virtual tool, which is used to control an actual scalpel (or other device) at a remote location. A tracking system employed by CASI consists of two magnetic-dipole antennae, one of which functions as a fixed transmitter (the operating table), the other a freely moving receiver (a scalpel). Both the transmitter and the receiver antennae consist of three mutually orthogonal coils with diameters wound as small as possible in order that each coil may be regarded as an infinitesimal dipole. A pulse of current is sent into the transmitter coils. This creates a magnetic field which induces currents in the receiver coils. These are connected to a signal processing device made by Polhemus, Inc. Enough information is provided to the device to solve for six unknowns: x, y, z, azimuth, elevation, and roll.[20]

The performance of the tracking device has an appreciable effect upon the smoothness of response of the entire simulator system. If the resolution and accuracy are poor, the device will prove to be of little use for the ultra-fine manipulation required for surgical procedures. If the latent period is too long, with the addition of the latent periods of all the other components involved in the system, the response of the simulation may lag too much to be usable in real time.

The audio feedback signal is generated by converting a continuous function of the surgical instrument position and orientation with respect to a 3D model into MIDI device instructions. These are instructions for controlling the dedicated audio synthesis portion of the hardware. These instructions do not convey waveforms, but convey control instructions, such as turning a bank of oscillators on or off, employing one of a number of possible preset waveform tables, to set the pitch of a bank of oscillators to one of 0-127 preset frequencies (i.e., a chromatic scale, or any contiguous series of frequencies roughly defined by an interval of an octave/12), or to increase or decrease the sum amplitude of a bank of oscillators to one of 0-127 possible preset amplitudes.

The controlling computer generates a stream of MIDI instructions using some predesigned "sonification" algorithm. This could be as simple as generating two continuous tones, one of which is fixed as a reference, where the other varies in pitch as a function of the error of a cursor in three-dimensional space with respect to some pre-planned trajectory (with the error calculated as the distance perpendicular to the desired trajectory). The user tries to correct for the error by minimizing the pitch interval between the tones.[18] Another scheme might be to generate foley effects (impact sounds) when a cursor crosses predefined three-dimensional object boundaries (such as a scalpel impacting bone). Pitch, amplitude, and waveform table parameters would change as a function of the impact force, cursor orientation (rotation vector), and modeled material properties of the surgical tool and tissue. The main issue here is one of user interface design; to decide which parameters of the interaction are important to the operator in performing the task, and how to represent this information so that it may be most intuitively grasped by the operator. This issue can best be addressed by careful examination of the entire task scenario, testing and re-engineering of candidate algorithms with constant input of potential users throughout the entire design process.

Can Virtual Audio Aid in the Exploration and Development of Space?

The surgical environment, like space, presents human beings with an environment that is often lacking in familiar reference points. For example, endoscopic surgery, which is performed through an instrument inserted into the body through a small incision, is a technique whose use is increasing. It presents both physical and sensory challenges to the physician. Surgeons must operate with remote-control devices, guided by flat video images, without haptic feedback from the organs and tissues being manipulated. Researchers at CASI are investigating ways in which sound cues can aid in orienting and guiding a surgeon who is telepresent within the patient's body. The authors propose to extend these techniques to space construction and surgery.

A major reason for using teleoperation in terrestrial surgery is the small size and delicate nature of structures in the body; for example, the retina. The motions of a surgeon often need to be kinematically reduced in both amplitude and force by a remote-control apparatus. A telepresence surgery system has been devised which can scale down the motion of the surgeon's hand by a factor of 100, so that 1 cm of hand motion moves the surgical apparatus by 0.1 mm.[21,22,23] For space-based construction of large structures, the motions of the operator may need to be kinematically amplified by this amount or more. A similar situation exists for sensory feedback. Microsurgery requires not only remote manipulation, but remote stereoscopic vision. Space-based construction can be seen as "macrosurgery," requiring stereo cameras mounted on a long baseline to extend the operator's depth perception.

The lag time caused by the processing of visual images will be exacerbated by speed-of-light delays if the operator is a significant distance from the construction site (say, Earth to geostationary orbit, or even Earth to Moon). Here, sound can function in a variety of ways. By reducing the bandwidth requirements, audio feedback can make teleoperation more feasible over a given distance, and can extend the distance over which teleoperation is practical. The operator may benefit from an intuitive sensory indication of the time delay. Multiple parallel independent channels of situational awareness information can be encoded in parallel musical "voices." Distance can be indicated by amplitude or pitch, and speed can be indicated by change in pitch (Doppler shift). Teleoperating from the Earth to the Moon can be performed in a manner similar to that of athletes, who must throw and catch a ball whose time of flight may be several seconds. A teleoperator on Earth may therefore be able to "throw" his/her intentions to an apparatus on the Moon; he/she can then "catch" the result as visual feedback is "thrown" back to Earth at the speed of light. This visual feedback can be enhanced with sound cues, so that the operator need not guess when the system is ready for another command. This may be especially important for teleoperation to (or from) a moving spacecraft. Over the course of an operation (surgical or otherwise) which lasts for several hours, a spacecraft moving at Earth-escape velocity may travel a sufficient fraction of a light-second. A teleoperator will have to continually readjust the pace of his/her reactions. Sound cues may be able to aid in this adjustment.

Many teleoperated tasks, particularly surgery, can benefit from haptic feedback. This must be limited to delays of no more than a few milliseconds. At first, it may seem that tasks involving haptic feedback are feasible over short distances only; say, between the surface of the Earth and low Earth orbit. However, it may be possible to increase the machine intelligence of the teleoperator's work station. It can be programmed to provide pre-determined responses that match the likely feedback expected from the remote end. As the true response is received, the work station can be programmed to learn from experience, and correct for discrepancies between expected and actual responses. Similarly, actions that require an immediate response can benefit from increased intelligence at the remote location of the "teleoperatee." We define the latter term as that which is affected by the actions of the teleoperator; it can be a machine(s), a human being(s), or a combination of both. The data stream from the teleoperatee may be images from an endoscopic camera, telemetry from patient monitoring equipment, or positional information from a robot arm used in space construction. The teleoperator will need to have this information presented in a manner that maintains his/her orientation relative to the task at hand, without causing sensory overload. Dividing the intelligence between the local and remote ends is similar to the way that the human body overcomes the limitations of the time-of-flight of nervous signals by the use of nerve ganglia and reflex loops to reduce the informational load of the distant brain (in this case, the teleoperator). Finally, a teleoperator can act as an avatar, or disembodied advisor, seeing, hearing, and feeling everything a teleoperatee experiences, except delayed in time. The avatar/operator can impart, by suggestion, gesture, and illustration, the essential information required to accomplish a task even when lagging many minutes behind the teleoperatee.

As the space infrastructure develops, this concept of "ganglia" or local nerve centers, can be extended further. For example, teleoperated robots can be deployed at various locations on the lunar surface for the purpose of geological surveys and prospecting.[24] The operator can be stationed on the Earth. A portion of the remote intelligence can be installed on a space platform at the L1 Libration Point (see Fig. 2). This can keep the robots small and light, while keeping time delays to a minimum. Furthermore, upgrades and repairs to the system can be performed at one location, rather than recalling the robots or deploying new ones. Fig. 2 shows a schematic diagram of the Earth-Moon system. The various locations in space may take on the role of nerve centers. The exact deployment of human beings and equipment will depend on the specific economic path that space development takes.

However, if teleoperation is a major factor, minimizing delays due to the speed of light will be important. It should be noted that the round-trip speed of light delays indicated in Fig. 2 are idealizations. In practice, some of these will be longer. In particular, transmitting information between a point on the Earth's surface to any orbit around the Earth will involve an indirect route involving numerous repeaters and stations on Earth and in orbit, in order to overcome the constraint of the Earth's rotation. A similar situation exists for non-stationary orbits. Thus, teleoperating from L5 to the Moon may be more feasible than teleoperating from the Earth to the Moon. However, it does not seem likely that a human habitat will be established at L5 just for the purpose of teleoperation. If such a habitat is built for, say, materials processing, however, it is a straightforward matter to station teleoperators there as well, perhaps with the L1 point serving as a local nerve center. (It should be noted that due to perturbations from the Sun's gravity, L4 and L5 are not stable points. However, there are stable regions which move in orbits about them [Ref. 4, page 127], so this should not significantly affect the teleoperation strategy. An object at L1 or L2 will be unstable in the direction of the Earth-Moon axis, but its position can be maintained by the use of thrusters.) The use of teleoperation can thus grow along with the rest of the space infrastructure.

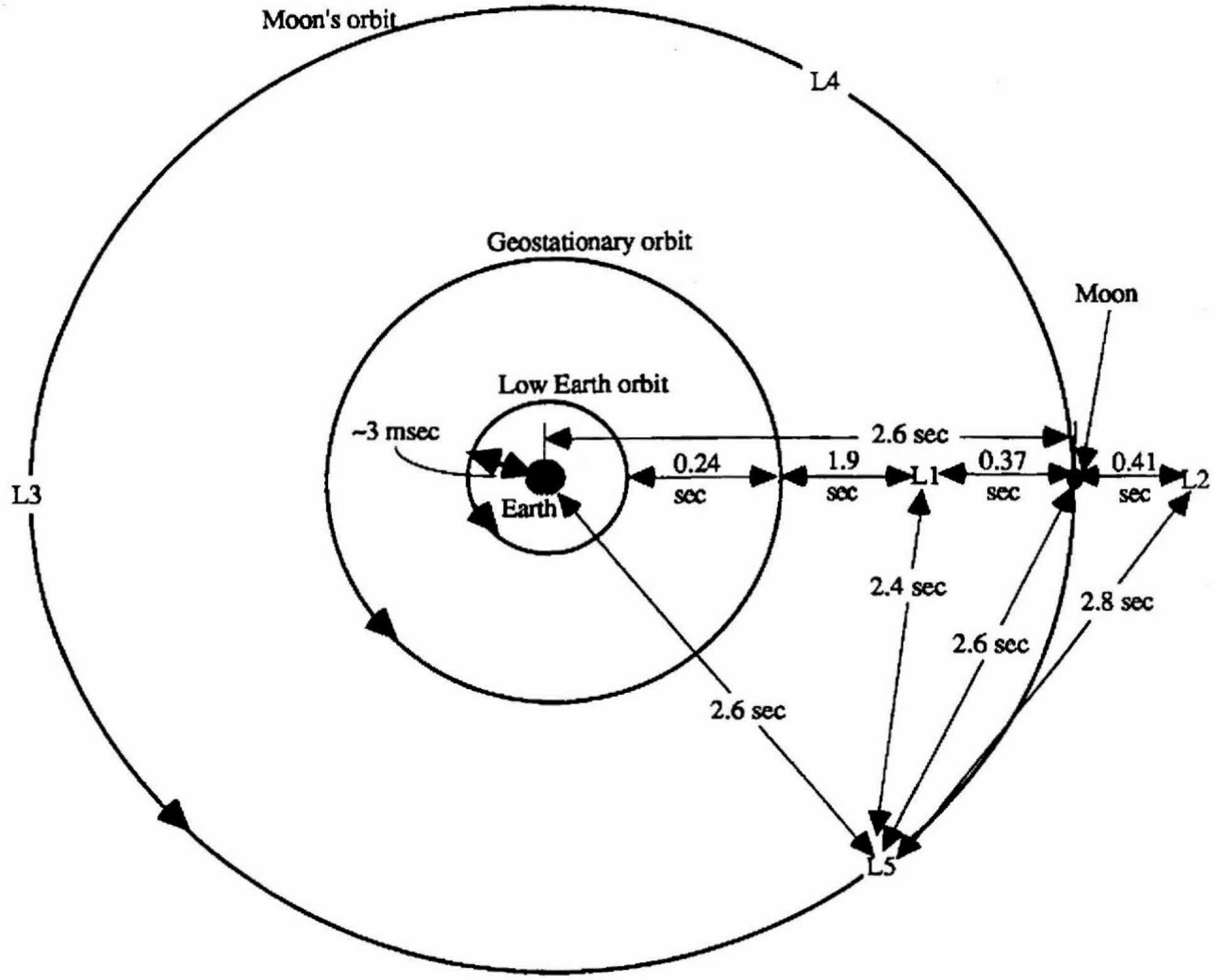

Fig. 2. Schematic illustration of the Earth-Moon system (not to scale). Prograde orbits are shown for an observer in the north celestial hemisphere. L1, L2, etc. represent the five Lagrange libration points. An altitude of 400 km was used for low Earth orbit. Times indicate round-trip velocity of light delays (idealizations which do not include further delays needed to relay signals to/from a rotating Earth or non-stationary orbits). Time delays between L4 and the other points shown are the same as those for L5. The Lagrange points can be used as nerve centers for a space teleoperation system.

Conclusions

Telepresence and virtual reality are among today's fastest-growing technologies. The immense throughput of data in teleoperation and virtual systems will likely increase as the technology progresses. The bottleneck in dealing with this data stream is, of course, the human brain. Rather than overloading the brain, teleoperation should make information management easier. The use of sound cues shows great promise in this area. Much of our effort to date has involved orienting the operator in the "inner space" of the human body. A logical extension of this work will be to adapt it for use in outer space. A near-term application may be the addition of sound effects to the virtual environment to substitute for the lack of sound in the vacuum of space. Adapting to the high frontier will require that human beings use their age-old capabilities in new ways. For example, it is common for astronauts to develop "space sickness." This is the nausea that results from conflicting sensory cues. The astronaut's eyes may provide a sense of up/down as a direction away or toward the feet. However, the vestibular sense from the inner ear provides no up/down sense without a gravitational gradient. We intend to investigate the use of sound cues to serve as a replacement for gravitational gradient cues in helping human beings orient themselves in space and avoid nausea. Appropriately, one function of the ear (hearing) may substitute for the other (the vestibular sense). Again, the precise auditory input used, the exact combination of human beings and machines that will prove to be optimal, and other specifics of the developing space infrastructure are difficult to predict. But we must prepare for life beyond the Earth by developing the means to effectively project our capabilities into a new environment.

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